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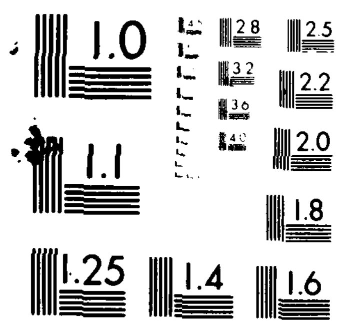

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AD A110843

An Investigation of Inhomogeneous Inelastic Deformations through Plate Impact Recovery Experiments and Mathematical Modelling of Propagating Localized Deformations

R.J. Clifton

January, 1982

U.S. Army Research Office
Grant No. DAAG29-80-K-0095

Brown University
Providence RI 02912

Report No. DAAG29-80-K-0095/F

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REPORT DOCUMENTATION PAGE

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1. REPORT NUMBER: DAAG29-80-K-0095/F
2. GOVT ACCESSION NO.: AD-A110843
3. RECIPIENT'S CATALOG NUMBER:
4. TITLE (and Subtitle): "An Investigation of Inhomogeneous Inelastic Deformations through Plate Impact Recovery Experiments and Mathematical Modelling of Propagating Localized Deformations"
5. TYPE OF REPORT & PERIOD COVERED: FINAL 10-5-80 to 10-4-81
6. PERFORMING ORG. REPORT NUMBER:
7. AUTHOR(s): R.J. Clifton
8. CONTRACT OR GRANT NUMBER(s): DAAG29-80-K-0095
9. PERFORMING ORGANIZATION NAME AND ADDRESS: Brown University, Providence RI 02912
10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS:
11. CONTROLLING OFFICE NAME AND ADDRESS: U. S. Army Research Office, Post Office Box 12211, Research Triangle Park, NC 27709
12. REPORT DATE: January, 1982
13. NUMBER OF PAGES: 9
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office):
15. SECURITY CLASS. (of this report): Unclassified
15a. DECLASSIFICATION/DOWNGRADING SCHEDULE:
16. DISTRIBUTION STATEMENT (of this Report): Approved for public release; distribution unlimited.
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report): NA
18. SUPPLEMENTARY NOTES: The view, opinions, and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other documentation.
19. KEY WORDS (Continue on reverse side if necessary and identify by block number): Dynamic plasticity, high strain-rate, pressure-shear impact
20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A high strain rate, pressure-shear experiment has been developed in which a thin specimen attached to an elastic anvil plate is impacted by an elastic flyer plate that is inclined to the direction of approach. This experiment can be used to obtain the plastic response of metals at strain rates of 10^5 s^{-1} and pressures of 2-8 GPa. Experimental results for 1100-0 aluminum, 6061-T6 aluminum and OFHC copper show the flow stress at strain rates of 10^5 s^{-1} to be much higher than at strain rates of 10^3 s^{-1}. For 1100-0 aluminum the effect of hydrostatic pressure

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on the flow stress has been examined by varying the angle of impact in order to change the ratio of the pressure to the shear stress. No significant pressure effect has been observed.

Problem Studied

This research has been directed towards understanding the plastic response of metals at high strain rates. Attention has been focused on the strain rate regime above 10^3 s^{-1} where a transition in the rate controlling mechanism has been reported by some investigators. From dislocation mechanics, as the applied shear stress increases the rate controlling mechanism is expected to change from the thermally activated motion of dislocations past obstacles to the viscous glide of dislocations between obstacles. For the former mechanism the plastic strain rate increases essentially exponentially with increasing shear stress whereas for the latter mechanism the plastic strain rate increases essentially linearly with increasing shear stress. So far, the development of models has not progressed to the point where one can predict the stress or strain rate at the transition. Furthermore, the models are not adequate for predicting either the sharpness of the transition or the response above the transition. Few experiments have been conducted at strain rates of 10^4 s^{-1} and above; furthermore, the interpretation of these experiments usually raises questions regarding inertia effects and the uniformity of deformation in the specimen. The objective of the present investigation has been to contribute to the understanding of the dynamic plastic response of metals by conducting experiments at strain rates 1-2 orders of magnitude higher than attained in most previous experiments. Interpretation of the experimental results has been made relatively straightforward by eliminating the effects of lateral inertia and end constraint.

The experiment developed for this investigation involves pressure-shear impact of thin (0.2 mm - 0.4 mm) plate specimens sandwiched between elastic, high impedance plates. A hard flyer plate (high strength steel or tungsten carbide) impacts a specimen backed by an anvil plate that is made from the same material as the flyer. The impact faces are parallel, but inclined relative to the direction of approach. Particle velocity and surface traction at the specimen-anvil interface are obtained from laser interferometric measurements of the normal and transverse components of the particle velocity at the free surface of the anvil plate. Shear stress and average shear strain rate in the specimen are deduced from the measured shear wave. Shear strain rates as high as 3×10^5 s^{-1} have been obtained. Variations of impact velocity and angle of inclination of the impact plane have been used to provide sufficient changes in the relative magnitudes of shear tractions and normal tractions to allow the effects of hydrostatic pressure on the flow stress to be evaluated.

In addition to the pressure-shear impact experiments there has been continued effort on the analysis of the formation of shear bands. Extensions have been made of the linear stability analysis based on investigation of the growth of small periodic perturbations of a homogeneous deformation. Limitations of this approach have been noted and attention has been shifted to computer simulation of nonlinear problems in order to understand the response under conditions for which instability is predicted when the linear stability analysis is used.

Principal Results

Twenty-seven high strain-rate, pressure-shear experiments have been conducted on 1100-0 aluminum specimens. Terminal shear strain rates in these tests varied from approximately 0.5×10^5 s^{-1} to 3.1×10^5 s^{-1}. Maximum shear strains varied from approximately 5% to 28%. Hydrostatic pressures varied from approximately 1.1 GPa to 2.9 GPa. The shear stress in the specimen is observed to become essentially constant after enough time has elapsed for several reverberations

of elastic shear waves through the thickness of the specimen. This response is interpreted as indicating that nominally homogeneous states of stress are established in the specimens and that 1100-0 aluminum does not exhibit much strain hardening under these loading conditions and at the terminal strains in the various tests. A best least squares fit of a linear relationship between the measured final flow stress τ, the pressure p and the terminal strain rate $\dot{\gamma}$ is

$$\tau = 1.13 + 0.27 \times 10^{-5}(\dot{\gamma}-1.35 \times 10^{5}) + 0.00156(p-25.7) \qquad (1)$$

where the units of τ and p are kbars, and the units of $\dot{\gamma}$ are s^{-1}. Because of scatter in the experimental results and the difference in loading conditions for different tests the uncertainty in the coefficients in (1) is quite high. Nevertheless, one can conclude with reasonable certainty that at strain rates of $10^5\ s^{-1}$ and pressures of 20 kbar the flow stress of 1100-0 aluminum increases strongly with increasing strain-rate and that the effects of hydrostatic pressure are relatively unimportant.

Several dynamic stress-strain curves obtained in these experiments are compared in Fig. 1 with those obtained by Duffy and Frantz at lower strain rates. The latter curves have been shifted along the strain axis so that, for example, a shear strain of 5% in Fig. 5.1 corresponds to a shear strain of 7.5% in their paper. This shift is used to account for the plastic strain during the precompression which occurs in pressure-shear experiments. The marked increase in flow stress shown at high strain rates suggests that the rate controlling mechanisms at strain rates of $10^5\ s^{-1}$ differ from those at strain rates below $10^3\ s^{-1}$. The increase in flow stress is too great to be explained in terms of the mechanism of thermally activated motion of dislocations past obstacles that is understood to dominate at strain rates below $10^3\ s^{-1}$. On the other hand, the representation (1) does not appear to be consistent with a viscous drag model because of the large contribution from the constant terms. It appears that the actual response is affected both by the interaction of dislocations with obstacles and by the glide of dislocations between obstacles. Different levels of resolved shear stress on the different slip systems in a polycrystalline aggregate may be responsible for the response not being characteristic of a single rate controlling mechanism.

Eight experiments have also been conducted on 6061-T6 aluminum specimens and two on OFHC copper specimens. Dynamic stress-strain curves from these investigations are shown in Figs. 5.3 and A.4. Again marked increases in flow stresses are obtained for increases in strain rate from $10^3\ s^{-1}$ to $10^5\ s^{-1}$. More experiments are required before the effects of hydrostatic pressure can be assessed.

From photomicrographs of the cross-sections of deformed specimens for all three of the materials studied, it appears that shear bands are not formed. Furthermore, from micro-hardness tests conducted at various points across the thickness of the deformed 1100-0 aluminum specimens, it appears that the hardness after impact is essentially uniform through the thickness. This evidence is interpreted as indicating that strain localization did not occur during these experiments.

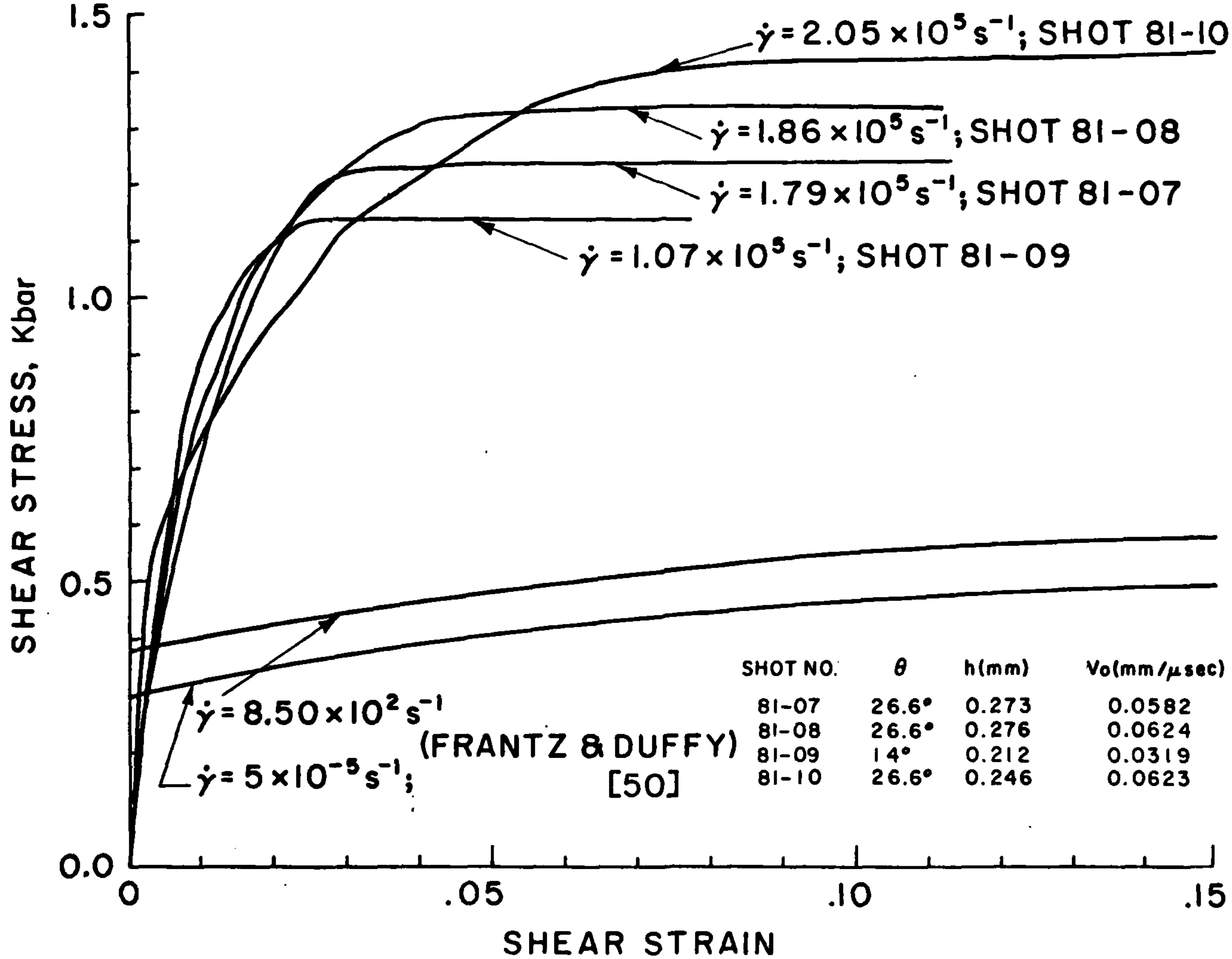

FIG. 5·1 DYNAMIC STRESS-STRAIN CURVES FOR 1100-O ALUMINUM AT P=28.1 Kbar

(From C.H. Li's Ph.D. thesis; θ is the angle of inclination of the target, h is the specimen thickness, and V_o is the projectile velocity. Ref. 50, Frantz, R.A. and Duffy, J., J. Appl. Mech. 39 (1972) 939.)

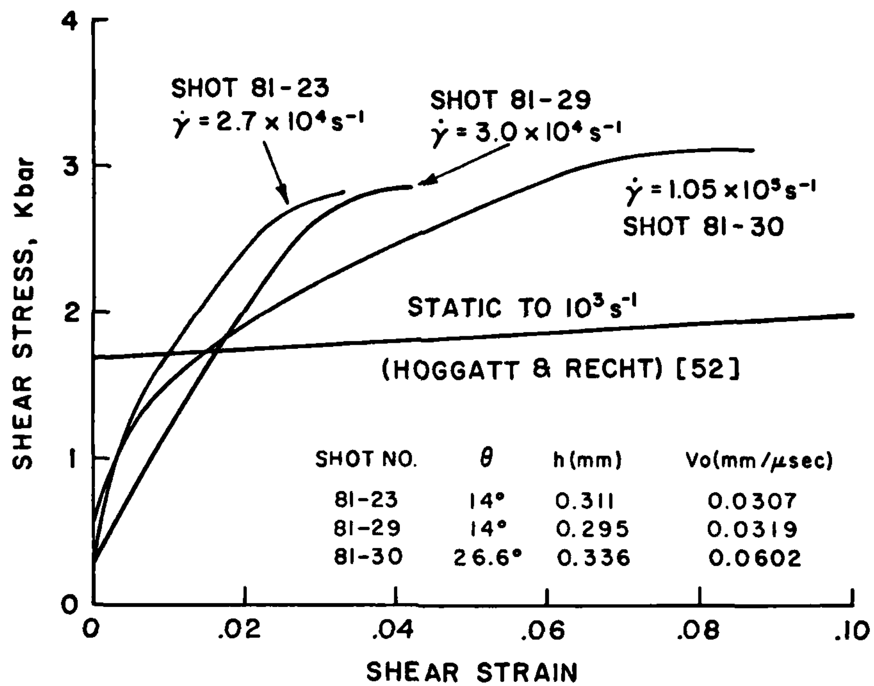

FIG. 5.3 DYNAMIC STRESS-STRAIN CURVES FOR 6061-T6 ALUMINUM AT P=28.2 Kbar

(From C.H. Li's Ph.D. thesis; θ is the angle of inclination of the target, h is the specimen thickness, and V_o is the projectile velocity. Ref. 52, Hoggatt, C.R. and Recht, R.F., Exp. Mech. 9 (1969) 441.)

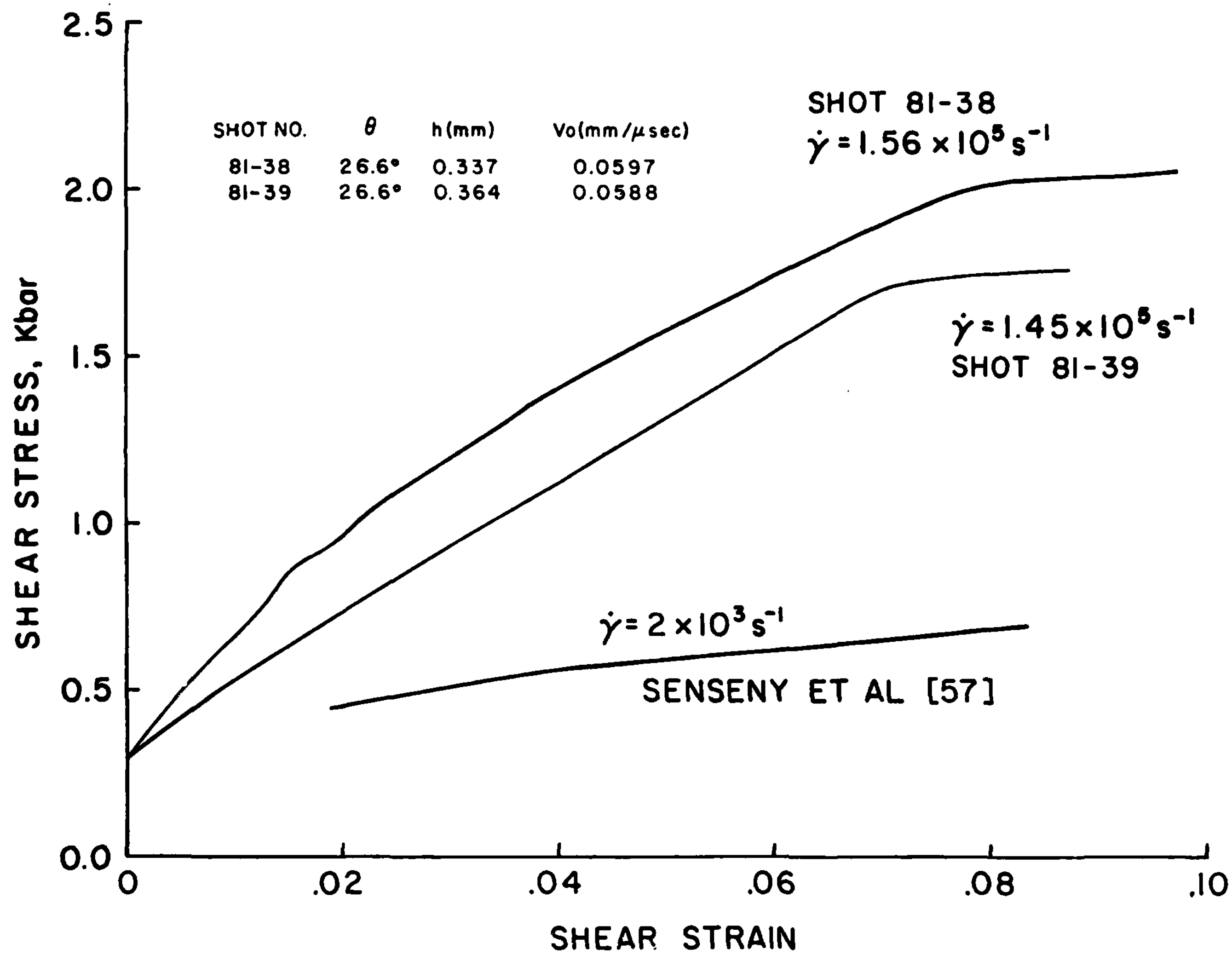

FIG. A·4 DYNAMIC STRESS-STRAIN CURVES FOR OFHC COPPER AT P=60 Kbar
(From C.H. Li's Ph.D. thesis; θ is the angle of inclination of the target, h is the specimen thickness, and V_o is the projectile velocity. Ref 57, Senseny, P.E., Richman, M.H., and Duffy, J., Brown University Report No. ARO-D-G 182/8.)

Publications

C.H. Li, and R.J. Clifton, "Dynamic Stress-Strain Curves at Plastic Shear Strain Rates of $10^5\ s^{-1}$" (Proceedings of the American Physical Society Topical Conference on Shock Waves in Condensed Matter held at SRI International in Menlo Park, California, June 23-25, 1981)

C.H. Li, "A Pressure-Shear Experiment for Studying the Dynamic Plastic Response of Metals at Shear Strain Rates of $10^5\ s^{-1}$", Ph.D. Thesis in preparation during reporting p. iod and accepted by Brown University on December 28, 1981; Abstract attached.

Scientific Personnel Suported by this Project and Degrees Awarded

R.J. Clifton, Professor of Engineering
C.H. Li, Research Assistant (Ph.D. degree requirements completed December 28, 1981)

E.S. Louvaris, Research Assistant
R.M. Reed, Technical Assistant

Abstract of

"A Pressure-Shear Experiment for Studying the Dynamic Plastic Response of Metals at Shear Strain Rates of 10^5 s^{-1}"

by Chin-Ho Li, Ph.D.

Brown University

December 1981

Development of a high strain rate pressure-shear plate impact experiment is described. The objective of such experiments is to determine the plastic response of metals at extremely high strain rates (so far up to 3 x 10^5 s^{-1}) under well controlled conditions. A thin specimen attached to an elastic anvil is subjected to pressure-shear loading by impact of an elastic flyer inclined to the direction of approach. After several wave reverberations between the two elastic plates, the state of stress in the specimen is essentially homogeneous. The strain rate can then be obtained as the velocity difference between the two faces of the specimen divided by the thickness of the specimen. The stresses in the specimen can be inferred from the particle velocity at the free surface of the anvil by means of elastic wave theory. The normal and transverse components of particle velocity are measured with a laser normal velocity interferometer (NVI) and a laser transverse displacement interferometer (TDI).

Experimental results for 1100-0 aluminum, 6061-T6 aluminum and OFHC copper show the flow stress at strain rates of 10^5 s^{-1} to be much higher than at strain rates of 10^3 s^{-1}. Investigation of the pressure effect on the flow stress in 1100-0 aluminum has been conducted by varying the angle of impact to change the ratio of the applied pressure to the applied shear stress. No significant pressure effect has been observed. Pressure effects in 6061-T6 aluminum and OFHC copper need further study.

Tungsten carbide, because of its high elastic impedances and its high yield strength, is shown to be a good material for the two elastic plates that bound the specimen. When tungsten carbide is used for these two plates it appears possible to study the dynamic plastic response of nearly all metals at strain rates of 10^5 s^{-1}.

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